Theoretical Model of Large Scale Rayleigh-Taylor Instability In Hall Effect Thrusters with High Specific Impulse

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Abstract: Rayleigh-Tailor instability is the most dangerous one in Hall Effect Thrusters (HETs). If the instability localized along all acceleration layer, it leads to drastic increasing an electron current in discharge. In Morozov's HET, Rayleigh-Tailor instability is suppressed within so-called positive gradient of the magnetic field and can exist after peak of the magnetic field and also in intensive ionization area and near anode. In the paper, the features of Rayleigh-Tailor instability in the new area of parameters, which is intrinsic in the modern thrusters and which is not covered by existing models, are theoretically considered. The study is carried out in two-fluid dissipative-less MHD approximation. The electron inertia is taken into consideration. It is shown that large enough specific impulses and moderate values of the magnetic field inductions as time of crossing the acceleration layer by the ions is less than a period of the lower-hybrid oscillation, Rayleigh-Tailor instability does not arise even in the magnetic field with the negative axial gradient. This result explains a penetration of a rather strong electrical field in the area beyond the acceleration channel, which is experimentally observed in some operation modes of the modern thrusters, and can be used at the development of wall-less HETs with high performance.

I. Introduction

AMONG plasma instabilities in Hall Effect Thrusters (HETs), Rayleigh-Tailor instability, which was first investigated in Ref. 1, occupies the special place. If the instability is localized along the entire length of the acceleration layer, it results in drastic increasing the electron current in the discharge that, in turn, leads to a sharp reduce of the efficiency of the thruster. In Morozov's HET, Rayleigh-Tailor instability is suppressed within the so-called positive axial gradient of the magnetic field and can exist in the area after the peak of the magnetic field induction and also in intensive ionization area and near the anode. The modern stage of the HET developments exhibits a great diversity of the thruster powers, specific impulses, geometrical sizes, configurations and magnitudes of the magnetic field. The available theoretical models of the Rayleigh-Tailor instability in HET[1-5] do not take into account all diversity of conditions in which the modern thrusters operate. This restricts the potentialities of these models to correctly describe the physical processes in the modern HETs and reduces their predictive power.

The present paper is devoted to the theoretical analysis of Rayleigh-Tailor instability features in the area of the parameters, which is inherent in the modern thrusters with the relatively high specific impulse (≥ 1700 s), and which is not covered by the previous theoretical models.

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II. Two dimensional theoretical model

The study of plasma stability is carried out in two-fluid magneto-hydrodynamic approximation with could magnetized electrons and cold non-magnetized ions.The perturbations of the plasma are assumed to be two-dimensional, quasineutral, and potential. The electron inertia is taken into account. The dissipative and ionization processes are neglected. The large scale perturbations ($k_x \sim 1/d_N, 1/d_B$) are considered. Hereafter, k_x, d_N, d_B are the projection of wave vector on the axis of the thruster, non-uniformity scales of the density and magnetic field, respectively. The unperturbed velocity of ions is assumed to be large enough so that $k_x V_0 \sim \omega_{lh}$, where ω_{lh} is the lower hybrid frequency. We use Cartesian coordinates with the X and Z axes directed along the directions of the unperturbed ion velocity and the applied magnetic field, respectively. Under these assumptions, linearized MHD equations take the following form:

$$\frac{\partial V_x}{\partial t} + V_0 \frac{\partial V_x}{\partial x} + V_x \frac{\partial V_0}{\partial x} = -\frac{e}{M}\frac{\partial \Phi}{\partial x} \tag{1}$$

$$\frac{\partial V_y}{\partial t} + V_0 \frac{\partial V_y}{\partial x} = -\frac{e}{M}\frac{\partial \Phi}{\partial y} \tag{2}$$

$$\frac{\partial n}{\partial t} + n_0 \frac{\partial V_x}{\partial x} + V_0 \frac{\partial n}{\partial x} + V_x \frac{\partial n_0}{\partial x} + n \frac{\partial V_0}{\partial x} + n_0 \frac{\partial V_y}{\partial y} = 0 \tag{3}$$

$$\frac{\partial u_x}{\partial t} + u_0 \frac{\partial u_x}{\partial y} = \frac{e}{m}\frac{\partial \Phi}{\partial x} - \frac{e}{m} u_y B_0 \tag{4}$$

$$\frac{\partial u_y}{\partial t} + u_0 \frac{\partial u_y}{\partial y} = \frac{e}{m}\frac{\partial \Phi}{\partial y} + \frac{e}{m} u_x B_0 \tag{5}$$

$$\frac{\partial n}{\partial t} + u_x \frac{\partial n_0}{\partial x} + n_0 \frac{\partial u_x}{\partial x} + n_0 \frac{\partial u_y}{\partial y} + u_0 \frac{\partial n}{\partial y} = 0 \tag{6}$$

Where Φ - the perturbation of potential,

V_x - the projection of ion velocity perturbation on axis X ,

V_y - the projection of ion velocity perturbation on axis Y,

n - the perturbation of number density of ions (electrons),

e - the unit positive charge,

u_x, u_y - the projections of electron velocity perturbation on X and Y axes, respectively,

m, M - the mass of electron and ion, respectively,

B_o - the induction of magnetic field,

V_0, u_0, n_0 - the unperturbed ion velocity, electron drift velocity, and number density of ions (electrons), respectively.

The set of Eqs. (1) – (6) is solved with the use of a short-wave approximation. Strongly speaking, this method should be applied for the perturbations, the scale of which is much less than a scale of plasma and magnetic field non-uniformity, which in the case of Hall thruster is approximately equal to a thickness of the acceleration layer d , whereas our interest is consideration of the perturbations with sizes, comparable to the thickness of the acceleration layer. Nevertheless, all experience in plasma physics shows that results of short-wave approximation are applicable, at least qualitatively, up to $k_x d \sim 1$ (See, for example, Ref.6). However, at the use of the short-wave approximation, it is possible to lose the effects due to boundary conditions. As is shown in Ref.7, the boundary conditions in Hall thrusters can be the reason of ion beam instability. This point will be discussed later.

At the use of a short wave approximation, Eqs. (1), (3) are reduced to the following:

$$\frac{\partial V_x}{\partial t} + V_0 \frac{\partial V_x}{\partial x} = -\frac{e}{M}\frac{\partial \Phi}{\partial x} \tag{1a}$$

$$\frac{\partial n}{\partial t} + n_0 \frac{\partial V_x}{\partial x} + V_0 \frac{\partial n}{\partial x} + n_0 \frac{\partial V_y}{\partial y} = 0 \tag{3a}$$

We seek the solution of a set of Eqs. (1a), (2), (3a), (4)-(6) in the form:

$$\mathbf{F}(t,x,y) = \mathbf{F}_j e^{-i(\omega t - k_x x - k_y y)} \tag{7}$$

Where $\mathbf{F}$ is the vector of perturbed parameters,

$\mathbf{F}_j$ is the vector of Fourier components of perturbed parameters,

k_y - the projection of a wave vector on the Y axis.

As a result, we obtain the following dispersion equation:

$$-\frac{1}{(\omega - k_x V_0)^2} + \frac{1}{\omega_{Be}\omega_{Bi}} - \frac{k_y}{k_\perp^2(\omega - k_y u_0)\omega_{Bi}}\left(\frac{1}{d_N} - \frac{1}{d_B}\right) = 0 \tag{8}$$

Where $\omega_{Be} = \dfrac{eB_0}{m}$, $\omega_{Bi} = \dfrac{eB_0}{M}$, $k_\perp^2 = k_x^2 + k_y^2$, $d_N = \dfrac{1}{\dfrac{d(\ln n_0)}{dx}}$, $d_B = \dfrac{1}{\dfrac{d(\ln B_0)}{dx}}$.

(At obtaining Eq.8, we took into consideration that $|\omega|^2 << \omega_{Be}^2$)

Using the assumption that $|\omega| << |k_y u_0|$, (9)

the validity of which will be shown below, and introducing d_{NB} such that $1/d_{NB} = 1/d_N - 1/d_B$, we can transform Eq.(8) to the following:

$$(\omega - k_x V_0)^2 = \frac{k_\perp^2 u_0 \omega_{Bi} d_{NB}}{\dfrac{k_\perp^2 u_0 \omega_{Bi} d_{NB}}{\omega_{Be}\omega_{Bi}} + 1} \tag{10}$$

Because $u_0 < 0$, from Eq.(10), it follows that at $d_{NB} > 0$ and $|k_\perp^2 u_0 \omega_{Bi} d_{NB}| < \omega_{Be}\omega_{Bi}$, we have instability with the following circular frequency and growth rate

$$\omega_r = k_x V_0, \quad \gamma = \sqrt{\frac{k_\perp^2 u_0 \omega_{Bi} d_{NB}}{\dfrac{k_\perp^2 u_0 \omega_{Bi} d_{NB}}{\omega_{Be}\omega_{Bi}} + 1}} \tag{11}$$

The condition $d_{NB} > 0$ means that the induction of the magnetic field decreases along the applied electric field faster than the ion density decreases or the density of ions grows faster in the direction of the electrical field than magnetic field.

In conventional Hall thrusters, the first situation takes place in the exit of a thruster, that is, after the peak of the magnetic field and can take place in the near-anode region, where the inverse direction of the electrical field is observed. The second situation can occur in the area of intense ionization of the propellant.

However, if

$$|k_\perp^2 u_0 \omega_{Bi} d_{NB}| > \omega_{Be}\omega_{Bi}, \tag{12}$$

then, independently on sign of d_{NB}, the instability is absent.

Let us consider the obtained result in more detail. Taking into account that $u_0 = -E_0/B_0$ and a minimal value of k_x, equal to π/d, which corresponds to half of a wave on the thickness of the acceleration layer, is significantly larger a minimal value of $k_{y_{\min}}$, which is equal to $1/r_0$, we can write:

$$\frac{\left|k_\perp^2 u_0 \omega_{Bi} d_{NB}\right|}{\omega_{Be}\omega_{Bi}} \cong \frac{\left|\pi^2 e E_0 d_{NB}\right|}{d^2 M \omega_{Be}\omega_{Bi}} \tag{13}$$

where E_0 - the strength of applied electrical field, r_0 - the middle radius of acceleration channel.

From inequality (12), with taking into account Eq. (13) and assuming that $\left|d_{NB}\right| \approx d$, it follows that at $d_{NB} > 0$ Rayleigh-Tailor instability is suppressed if

$$\alpha = \frac{\sqrt{\omega_{Be}\omega_{Bi}}\, d}{V_{0av}} < \pi \tag{14}$$

Here $V_{0av} = \sqrt{\frac{eE_0 d}{M}}$ - some average velocity of ions in the acceleration layer.

The condition (14) of Rayleigh-Tailor instability suppression is identical in form to the condition of suppression of quasipierce ion beam instability in Hall thrusters[7]. This fact is of interest in itself. Besides, since quasipierce ion beam instability is due to available of boundaries where perturbations of electrical potential become equal to zero, the same conditions for the suppression of two different instabilities allow to expect that taking into account the boundaries at an analysis of Rayleigh-Tailor instability will not lead to essential change in threshold of the instability.

The substituting of parameters, which are real for modern HETs, into ω_r and γ (Eqs.11), confirms inequality (9), excluding the nearest vicinity of the singularity in γ.

Let us consider a sample, related to the experimental model CAMILA HT-55[8]. At a magnetic induction of 0.015 T and thickness of the layer $7\cdot10^{-3}$ m, a threshold of the average velocity, according to Eq.(14), is $1.2\cdot10^4$ m/s. In this case, the velocity of ions in the end of the acceleration layer $V_{0d} = \sqrt{2}\cdot V_{0av}$ equals to $1.7\cdot10^4$ m/s. At the discharge voltage $U_d = 300\,\mathrm{V}$, the theoretical value of the average velocity (V_{0av}) of single charged ions is $1.49\cdot10^4$ m/s that is higher than a threshold value. For this value of the average velocity, $\left|\omega\right| \approx \left|k_x V_{0av}\right|$. A maximum of k_x is $k_{x\max} \cong 1/h_c$, where h_c is the height of electron cycloid.

$$h_c = \frac{2E_0 m}{eB_0^2} \tag{15}$$

Then, for $r_0 = 2.15\cdot10^{-2}$ m and other parameters of the experimental model CAMILA HT-55, noted above, we have for a maximum of ratio $\left|\omega\right|/\left|k_y u_0\right| \approx \left|k_{x\max} V_{0av}\right|/\left|k_{y\min} u_0\right| = 0.052 \prec\prec 1$

III. Numerical Solving Boundary Eigenvalue Problem for Model Example

The theoretical model, considered in Sec. II, does not take into account boundary conditions and strongly speaking requires only small changes of the unperturbed parameters within a wave. Here, we consider more realistic model, using numerical solving the boundary eigenvalue problem for a model example. We use the set of linearized Eqs.(1)-(6) to which add the following boundary conditions for the perturbations:

$$\Phi(0) = \Phi(d) = 0;\ n(0) = 0;\ V_x(0) = 0;\ V_y(0) = 0. \tag{16}$$

The needed condition for arise of Raleigh-Tailor instability $d_{NB} > 0$ is simpler to provide suggesting that $B_0 = const$ and undisturbed density of ions (electrons) increases along the channel (layer). In doing so, in order to avoid introducing the effects like ionization, which should increase the density of ions (electrons) in spite of the acceleration of the ions, we apply the following approximate method. At $x = 0,$ the ions have unperturbed velocity V_{00}. As the ions move along the layer, their energy reduces by 30% by an applied opposing uniform electrical field. As a result, the unperturbed density of plasma increases along the layer. However, in the equation of continuity for electrons (6), the sign of u_0, we leave such that corresponds to the positive sign of the electrical field.

The solution of boundary eigenvalue problem (1)-(6), (15) is sought in the form:

$$\mathbf{F}(x, y, t) = \mathbf{F}_J(x)e^{-i(\omega t - k_y y)} \tag{17}$$

Further, the obtained set of ordinary differential equations, is solved, as in Ref.7, with the use of the shooting method combined with so-called global-converging Newton-Ralphson iteration procedure. The inequality (9) was used as well.

The solutions were obtained for $d = 10^{-2}\,\mathrm{m},\ k_{y\min} = 1/r_0 = 23.5\,\mathrm{m}^{-1}$ and for twelve values of α_m in the range 0.5π to 1.7π. The parameter α_m differs from the parameter α, defined by (14), by using V_{0d} -the unperturbed ion velocity in the end of the layer instead of V_0.

The conducted numerical modelling shows that really there is a threshold for Rayleigh-Tailor instability lower which the instability is absent. In the conducted numerical modelling, the instability is suppressed at $\alpha_m < 0.79\pi$ which is very close to the threshold value of α in Eq.(14) especially if to take into account some difference between α_m and α. As for a circular frequency and the growth rate, we have the following. The singularity in rather large vicinity of the threshold value of α_m, namely, at $0.5\pi < \alpha_m < 0.9\pi$ is not observed. The fast growth of γ starts from $\alpha_m \cong \pi$. As a distinction from the analytical model 1) the growth rate of the instability at α_m lower the threshold value does not vanish, but become negative; 2) the frequency ω_r in the noted above vicinity of α_m is close to zero, that is, the instability is aperiodical. These two features of the instability are a consequence of taking into consideration of the boundary conditions.

IV. Discussion of investigation results

The condition of the suppression of the instability (12) can be brought to one further form. From inequality (12) using the same assumption as at obtaining inequality (14), we have the following inequality:

$$\frac{\pi^2 E_0 m}{d B_0^2} > 1 \tag{18}$$

Applying an expression for the height of electron cycloid (15), we can transform the inequality (18) into the following:

$$\frac{h_c}{d} > \frac{2}{\pi^2} \tag{19}$$

Thus, the suppression of Rayleigh-Tailor instability in this case is produced by a finite height of electron cycloid. If to formally introduce Larmor radius of electrons $\rho_{Lef} = v_{ef} / \omega_{Be}$, calculated on a velocity due to a drop of the potential in the acceleration layer

$$v_{ef} = \sqrt{2eE_0 d / m}\ , \tag{20}$$

then from inequality (18), it follows that the condition of the instability suppression transforms as is shown:

$$\frac{\rho_{Lef}}{d} > \frac{\sqrt{2}}{\pi} \tag{21}$$

It is of interest to compare the obtained results with another approach to suppress Rayleigh-Tailor instability in the magnetic field which reduces in the direction of the electric field. The approach was developed in Dnepropetrvsk State University (Ukraine) in the ‘80s of last age (See, for example, Ref. 9). Based on this approach to suppression of the instability, first wall-less Hall Effect accelerators and thruster were developed and experimentally investigated[9-12]. They received the name outside electric field accelerator (OEFA) and outside electric field thruster (OEFT), respectively. In these devices, the acceleration of the ions was produced in dropping magnetic field. The devices had a very small power: 1 to 60 W and those of them, which were intended for practical applications possessed small sizes and mass as well. The precise enough experiments showed that if parameters of the accelerators met the requirements of suppression of Rayleigh-Tailor instability, then the fraction of ion current in the discharge current was close to 100 % as the ions leaved the acceleration area[9]. Unfortunately, as a consequence of decay of the Soviet Union, the problems with funding the works on OEFA-OEFT arose and in the mid-‘90, the works were stopped. Currently, the interest to the wall-less thrusters with the acceleration ions in the dropping magnetic field is renewed[13].

In OEFA-OEFT according to a theoretical model[9], the suppression of Rayleigh-Tailor instability occurs owing to reducing the ion current density until the level at which

$$\left|k_\perp^2 u_0 \omega_{Bi} d_{NB}\right| > \omega_{pi}^2 \qquad \text{(in terms of this paper),} \qquad (22)$$

where $\omega_{pi} = \sqrt{\dfrac{n_0 e^2}{\varepsilon_0 M}}$ - the ion Langmuir frequency,

ε_0 - the dielectric constant.

In Ref. 9, it is shown that the condition (21) corresponds to the density of ion current, which is described by Child-Langmuir’s formula but with coefficient, which is an order of magnitude larger. Besides, the condition (22) is equivalent to the following:

$$\frac{D_i}{d} > \frac{\sqrt{2}}{\pi} \qquad (23)$$

Where D_i - the Debye radius of ions, calculated on the drop of the potential in the acceleration area.

(In inequality (23), as distinction from Ref. 9, a minor correction due to possible small violating the quasineutrality of the non-disturbed plasma is omitted.) Taking into consideration that Debye radius of single charged particles depends on density of plasma and their energy only, we can formally, instead of inequality (23), write the following:

$$\frac{D_e}{d} > \frac{\sqrt{2}}{\pi} \qquad (24)$$

Where D_e - the Debye radius of electrons, calculated on the drop of the potential in the acceleration layer.

Comparing inequalities (21) and (24), we see their full symmetry.

It is necessary to note the following. The threshold velocity reduces at decreasing a magnetic field. However, there are restrictions on reducing the magnetic field induction in Hall thrusters which due to 1) diamagnetism of plasma; 2) conductivity of plasma transverse to the magnetic field, produced by collisions of electrons with atoms and walls of the acceleration channel.

At comparison of the Rayleigh-Tailor instability suppression by finite Larmor radius and finite Debye radius of electrons, we can also note the following. On the one hand, the maximal density of the ion current at the suppression of Rayleigh-Tailor instability by finite Larmor radius is significantly larger than at the suppression by finite Debye radius, and on the other hand, by finite Debye radius, all ion-electron instabilities are suppressed, whereas, by finite Larmour radius, we cannot, probably, suppress high frequency (with $\omega \sim \omega_{pi}$) ion-electron instabilities, type of Bernstein mode, which are not so dangerous as Rayleigh-Tailor instability, but, can, probably, provide a fraction of an electron current in the discharge current at a level of around 10 %.

Thus, the conducted investigations have led to essential modifications of the conditions of the Rayleigh-Tailor instability initiation. From the new model, it follows that at large enough specific impulses and moderate values of the magnetic field induction at which the time of crossing the acceleration layer by the ions is less than a period of the lower-hybrid oscillation, Rayleigh-Tailor instability does not arise even in the magnetic field with the negative axial gradient. This fact, probably, explains a penetration of a rather strong electrical field in the area beyond the acceleration channel, which is experimentally observed in some operation modes of the modern thrusters, in particular, in CAMILA Hall thrusters[8] since at the suppression of Rayleigh-Tailor instability, the electrical resistance of a fraction of the acceleration layer in dropping magnetic field should sharply increase.

The results of the theoretical investigations can be used for reducing losses of ions on acceleration channel walls of HET by "expulsion" of a significant part of the acceleration layer from the channel. This should increase the performance of the thruster and its lifetime. The results of investigations can be applied also in developing a wall-less thruster with the high performance.

Conclusion

1. The two-dimensional theoretical model of Rayleigh-Tailor instability with taking into account inertia of electrons was developed.

2. From an analytical consideration, it follows that there exists a threshold, defined by a combination of thruster parameters, lower of which the instability is absent even in the magnetic field with the negative axial gradient. The instability is suppressed at large enough specific impulses and moderate values of the magnetic field inductions as time of crossing the acceleration layer by the ions is less than a period of the lower-hybrid oscillation.

3. The numerical solving the boundary eigenvalue problem for a model sample confirms available of a threshold of the thruster parameters combination lower of which the instability is absent. The numerical value of the instability threshold and the order of the growth rate magnitude are close to the results of the analytical consideration. Whereas, there are the essential differences in the frequencies of the waves, excited by the instability and in behavior of the growth rate lower the instability threshold. These differences are due to taking into account the boundary conditions at numerical modelling.

4. The factor, which provides the suppression of Rayleigh-Tailor instability, is a finite height of the electron cycloid in applied electrical field (finite Larmor radius of electrons, calculated on an applied difference of the potential).

5. The suggested theoretical model of Rayleigh-Tailor instability explains the fact of a penetration of the essential electrical field in the area after the peak of the magnetic field induction.

6. The comparison between suppression of Rayleigh-Tailor instability by finite Larmor radius of electrons and by finite Debye radius shows that they distinct by different requirements to the density of ion current. This defines the possible areas of applications. The first approach to the suppression of the instability is preferable for HETs of small, middle, and large powers, the second – for HETs of very small powers, in which nano-satellites need.

7. The results of the investigation can be used for reducing losses of ions on acceleration channel walls of HET by "expulsion" of a significant part of the acceleration layer from the channel and also in developing a wall-less thruster with the high performance.

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